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Analyzing the Acoustic Performance of Unglazed Terracotta in an Indoor Office Environment

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Abstract
Work environments commonly address users' thermal, visual, and spatial comfort; however, acoustic comfort tends to be neglected, leading to potential discomfort. Terracotta, a durable indigenous material deeply ingrained in Indian households for centuries, is conventionally utilized in constructing roofs, floors, and decor but remains unexplored for its acoustic attributes. This study evaluates the acoustic performance of unglazed terracotta tiles as a salutogenic resource, employing the reverberation room method (ASTM C423) and the impulse response method (ISO 3382-2) in an indoor office space. Parameters such as sound absorption, background noise, sound pressure level, Speech Transmission Index (STI), Reverberation Time (RT), and noise curves are meticulously measured both pre- and post-placement of terracotta specimens using a Bedrock SM90 Class 1 Sound Level Meter. The findings from this research aim to encourage architects to consider terracotta as a prospective material for enhancing acoustic conditions within built environments. Upon analyzing the reverberation, speech intelligibility, background noise, signal-to-noise ratio, and noise curve evaluations, it was observed that terracotta demonstrates high effectiveness as a panel absorber, especially in higher frequency ranges. Further improvements were noted when the panels were given a foam backing, suggesting potential as an effective acoustic panel.

Keywords*:* Acoustics; Office Setting; Terracotta; Speech Transmission Index (STI); Reverberation Time.

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1. Introduction

Noise pollution, an often-overlooked form of environmental pollution, has become a significant concern in modern societies. The rapid advancement of technology and urbanization has increased noise levels from various sources, including electronic appliances, airplanes, traffic, heating, ventilation, and air conditioning (HVAC) systems. These sources generate high sound pressure levels inside and outside buildings, contributing to a pervasive noise environment. According to Fontoba-Ferrándiz et al., 2020, noise pollution disrupts daily life and poses serious health risks, such as stress, hearing loss, and cardiovascular issues.

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Modern workspace requirements are constantly changing, and there is a constant need to adapt to the needs of employees and provide built comfort for maximum work efficiency (Caradonna, R., 2023). In the research conducted in office spaces by Hodgson M in 2008, it was discerned that occupants are not satisfied with the excessive noise and poor speech privacy. The research concluded that their acoustic environment did not enhance their ability to work. Studies by Alomani A. et al. in 2021 reported that employees spend half of their waking hours in office spaces, making the comfort and health of occupants highly crucial. It is important to stress that noise is a direct threat to human health, and new explorations need to take place in the context of acoustics and built environment to reduce undesirable outcomes by architects and acousticians (Trocka-Leszczynska, E et al., 2021). Acoustics is the quality of a room or building that helps determine how sound is transmitted in it. Workplace acoustic comfort must be a part of the mandatory framework of corporate social responsibility (Mahbub et al., 2010). We must address the acoustic comfort of workers in office spaces as they lead to undesirable mental and physical health consequences.

The research aims to demonstrate whether unglazed terracotta can perform as an effective acoustic material, and as a sustainable alternative for commercially available ones. Through a comprehensive analysis of six aspects including sound absorption coefficient, reverberation time, speech intelligibility index, background noise analysis, signal-to-noise ratio, and noise curve evaluation, the paper aims to create a methodology to delve deeper into the acoustic performance of terracotta in an office space.

1.1. Need

Office spaces, particularly open-plan offices, are significantly impacted by multiple sources of noise throughout the workday, including HVAC systems, ambient background noise, and human interactions. Elevated noise levels in the workplace have been linked to increased adrenaline levels in employees, leading to heightened states of tension and stress. The work environment's physical setting can be considered a tool for achieving better employee performance in behaviour and efficiency (Lee et al., 2010). This underscores the necessity for comprehensive analysis, study, and remediation of the acoustic environment in office spaces, as Qi Mend et al. noted, 2021.

Despite being at or near the existing background noise level, accumulating noise sources will collectively raise the overall noise level (Field et al., 2008). Acoustic panels are widely recognized as an effective method for noise control in built environments. However, many commercially available acoustic panels are not locally manufactured and pose health risks. For instance, while effective at sound absorption, glass wool, and rock wool materials can cause skin irritation and respiratory issues upon exposure (NPG. Suardana et al., 2019). Thus, there is a critical need for an informed approach to acoustic control that mitigates negative health impacts. Historically, asbestos-based materials were commonly used for their acoustic properties until their potential health hazards were identified. Subsequently, mineral-based fibrous materials like glass and rock wool fibers have been used as replacements. However, these materials also come with significant drawbacks, including high energy demands for manufacturing and challenges related to safe disposal post-usage (Arenad et al., 2020).

It has become increasingly important to analyze locally available materials for construction due to the socio-cultural and environmental benefits it provides (Alade et al., 2018). Indigenous materials are known to drastically reduce construction's overall energy consumption and environmental impact. In a study by Morel et al., 2001, it was observed that adoption of local materials decreased energy consumption by up to 215% and the impact of transportation by 453%.

One such locally available material is terracotta, which is widely used in building construction but whose acoustic properties have not been thoroughly analyzed. Terracotta is a natural clay-based material frequently used in construction for its durability and aesthetic qualities. This research aims to evaluate the acoustic properties of terracotta as a potential alternative to commercially available synthetic acoustic panels. Unglazed terracotta tiles are commonly used as terrace tiles due to their non-slippery nature and thermal properties. In research by Rambaldi et al. in 2015 to analyze the acoustic performance of ceramic tiles, it was observed that traditional terracotta tiles could be the base for creating modular products that can be applied in new buildings or retrofitted into existing buildings. The aesthetic significance and its sustainable characteristics make unglazed terracotta tiles a suitable material for research on acoustic performance in an office environment.

Modern acoustic panels, while effective, often involve synthetic materials such as glass wool and rock wool, which present health risks and environmental challenges. This creates a demand for sustainable, locally sourced alternatives. Unglazed terracotta, widely used in construction, remains underexplored for its acoustic potential. This research is necessary to evaluate terracotta's acoustic properties as a healthier, eco-friendly alternative to synthetic panels, addressing both the acoustic needs of modern offices and the imperative for sustainable building materials.

1.2. Research Question

Given the growing demand for sustainable materials in office spaces and the health concerns associated with synthetic acoustic panels, this study aims to explore the acoustic properties of unglazed terracotta. Specifically, the research addresses the question: How effective is unglazed terracotta in improving the acoustic performance of indoor office environments, with respect to reverberation time, speech intelligibility, and noise control, compared to conventional synthetic acoustic panels?

1.3. Aim

This research aims to advance the architectural acoustics field by applying unglazed terracotta, a sustainable and locally sourced material, thereby enhancing the quality of work and promoting health within indoor office environments. This endeavor seeks to harmonize terracotta's acoustic properties with modern office spaces' exigencies, providing a scientifically robust solution that addresses both environmental sustainability and human well-being.

1.4. Objective

This research endeavors to meticulously analyze the acoustic properties of unglazed terracotta to ascertain its suitability as an acoustic material within indoor office environments. The investigation is driven by two primary objectives: first, the comprehensive measurement of the acoustic properties of unglazed terracotta via a sound level meter (SLM) through detailed acoustical analysis, and second, the formulation of a comparative analysis contrasting the baseline scenario devoid of terracotta with the design scenario incorporating terracotta, to evaluate its acoustic efficacy and performance rigorously.

2. Materials and Methods

In an IEQ survey performed by Jensen et al., 2005, it was observed that out of the nine core satisfaction categories, poor acoustics caused the most significant dissatisfaction. It is identified that the amount of space, noise, visual intrusiveness, and lack of privacy are the critical factors that encompass workplace satisfaction (Bourikas et al., 2021). Acoustics defines experiential spatial conditions predominantly in constructed environments. It is important to design spaces sensitive to acoustics as a part of general building design, not just dedicated to musical and speech spaces (Foged et al., 2022; Pavithra et al., 2023). Greater attention has been focused on sustainable materials in the building sector. This comes with analyzing the acoustic and thermal performance to achieve a significant impact on the environment and human health (Ricciardi et al., 2014).

Indoor acoustic comfort can be achieved by mitigating room reverberation time and reducing sound transmission between confining environments (Neri et al., 2022). A study by Abdolreza et al., 2022 suggests that materials with high porosity have better sound absorption for acoustic wall tiles. Unglazed terracotta tiles were chosen for this study for their higher porosity. The findings can help us understand the office design’s effect on the occupants’ physical and mental well-being as we adapt to new and improved ways of living. The amount of space, noise, visual intrusiveness, and lack of privacy are commonly identified by employees as the critical factors for their lack of satisfaction with their workspace environment.

The office setting, particularly open-plan designs, typically experience various noise sources, such as HVAC systems, conversations, and ambient sounds. These environments often face challenges related to noise control, making it necessary to consider effective acoustic solutions. In this context, evaluating alternative materials like terracotta is crucial for creating quieter, more comfortable spaces that enhance employee well-being and productivity.

Acoustics is the science of sound, focusing on its production, propagation, and reception within different spaces. In the scope of this research, acoustics deals with optimizing sound environments in office spaces to minimize noise distractions and improve auditory comfort. Understanding acoustic principles is vital for evaluating materials like terracotta for their potential to improve sound quality in office environments. Key parameters used to assess acoustic performances are Speech Transmission Index (STI), Reverberation Time (RT60), and Signal-to-Noise Ratio (SNR). STI measures how clearly speech can be understood in a particular environment, with values ranging from 0 (poor intelligibility) to 1 (excellent intelligibility). In office environments, clear speech is essential for effective communication. This study uses STI to assess the impact of unglazed terracotta on speech intelligibility and how it compares to traditional acoustic materials. Reverberation time measures how long it takes for sound to decay by 60 decibels in a space. It is a critical factor in determining the acoustic quality of a room, as excessive reverberation can blur speech and increase noise levels. In this research, RT60 is measured to determine how unglazed terracotta affects sound reflections and reverberation in an office environment, compared to spaces without terracotta. SNR measures the strength of a desired signal compared to the background noise level. It is defined as the ratio of the signal power to the noise power, often expressed in decibels (dB). A higher SNR indicates a clearer signal relative to the noise, which is important for ensuring effective communication and evaluating acoustic performance. In acoustic studies, SNR determines how well speech or other sounds stand out from background noise in various environments.

2.1. Methodology

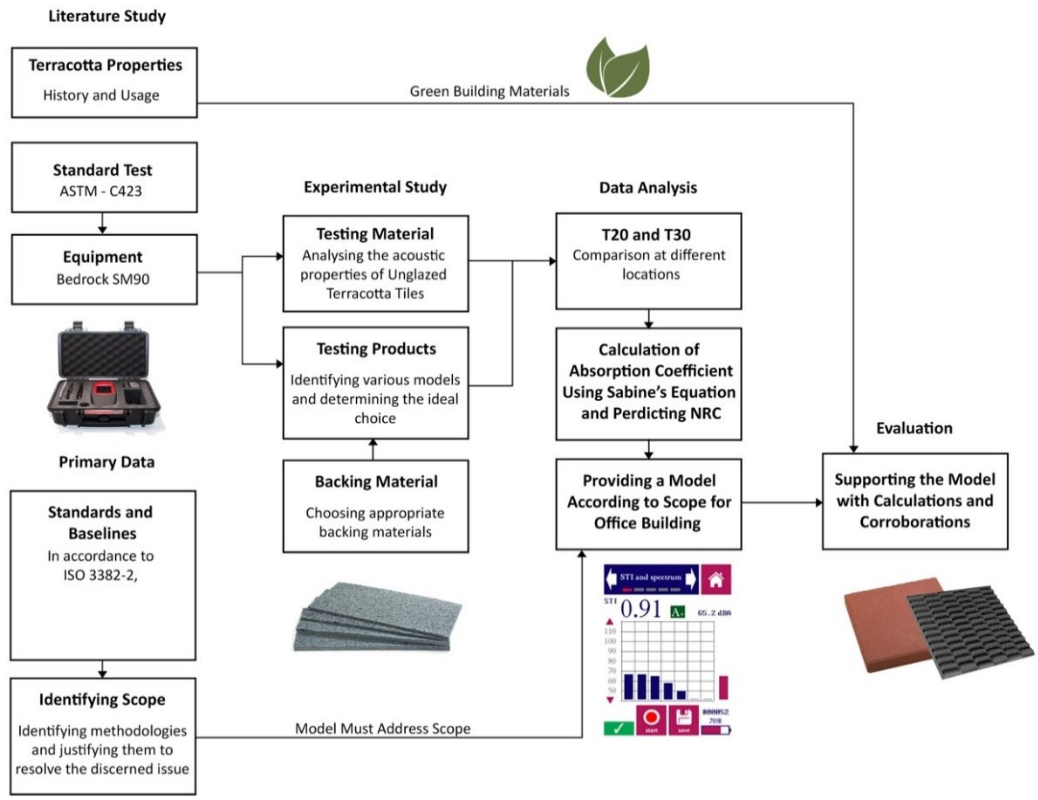


Figure 1. Research Methodology by Author(s).

The methodology for analyzing unglazed terracotta tiles, as depicted in Figure 1, encompasses a systematic exploration of the material's acoustic comfort properties to assess its impact on the overall acoustic quality of indoor office environments. This investigation employs standard acoustic tests utilizing a sound level meter to compare different scenarios. Based on established acoustic formulae, detailed calculations are performed to determine the absorption coefficient and other pertinent acoustic parameters. Furthermore, a design case incorporating unglazed terracotta is proposed to enhance the acoustic performance of the office space, providing a comprehensive evaluation of its potential benefits and effectiveness in real-world applications.

2.2. Standard Acoustical Tests

The standard tests conducted to analyze the acoustic properties of unglazed terracotta within an indoor office environment are outlined in detail as follows:

- Reverberation Analysis: The room's RT60 is measured per the standardized procedure outlined in ISO 3382-2. Utilizing the impulse response method, RT60 measurements are obtained by assessing the decay characteristics at various 1/3 octave bands. A clapper is employed to initiate the impulse response, and subsequent energy decay curves are plotted to quantify reverberation time accurately. Multiple measurements are undertaken to ensure the reliability and precision of the data.

- Speech Intelligibility Assessment: STI is evaluated using the STIPA Pro measurement technique to gauge speech intelligibility within the tested environment. A measurement duration of 60 seconds is adopted to enhance measurement accuracy. STI analysis is conducted across 1/3 octave bands from 125 Hz to 4000 Hz, comprehensively evaluating speech clarity and intelligibility.
- Background Noise Analysis: Frequency analysis of background noise is performed utilizing a Real-Time Analyzer (RTA) across 1/3 octave bands covering frequencies from 25 Hz to 20 kHz. Each reading is conducted over sixty seconds to accurately capture variations in background noise levels, facilitating a thorough assessment of ambient noise characteristics within the office environment.
- SNR Measurement: SNR measurements are conducted to analyze the speech intelligibility of the room, assessing the sound pressure level (SPL) of running speech about background noise levels. A talk box generates standardized speech samples, with each reading conducted over sixty seconds. SPL measurements of speech and background noise are obtained, allowing for the calculation of total LAeq and subsequent determination of SNR.
- Noise Curve Evaluation: Noise levels are assessed based on sets of standardized spectral curves, with Noise Criteria (NC) values derived to evaluate background noise within the room. The Bedrock SM90 system implements the NC version standardized through ANSI S12.2:2008, comprehensively assessing noise characteristics and facilitating comparisons against established noise criteria standards.

Table 1. List of Equipment Used by Author(s)

Instrument	Measured Parameters	Photos
Bedrock SM90 Class 1 Sound Level Meter	RT Speech Intelligibility Background Noise SNR NC	
Clapper – Impulse Noise Generator	RT	

In the context of this research, the Bedrock SM90 is employed to conduct a series of crucial measurements, including but not limited to STIPA Pro, NC Curve, LAeq, Speech level, and RTA assessments. Each measurement procedure adheres meticulously to the standards outlined by the American Society for Testing and Materials (ASTM) and the International Organization for Standardization (ISO), particularly referencing ISO 3382-2 standards for RT60 measurements. These standards ensure consistency and reliability in data acquisition, facilitating robust comparisons and analyses. List of equipment used in this study is tabulated in Table 1.

Upon acquiring the requisite data through the Bedrock SM90, a comprehensive analytical process ensues, wherein raw data is meticulously scrutinized, processed, and converted into graphical representations and numerical calculations. These analyses yield insights into various acoustic parameters, enabling a deeper understanding of the acoustic characteristics of the tested environment and the efficacy of unglazed terracotta as an acoustic material.

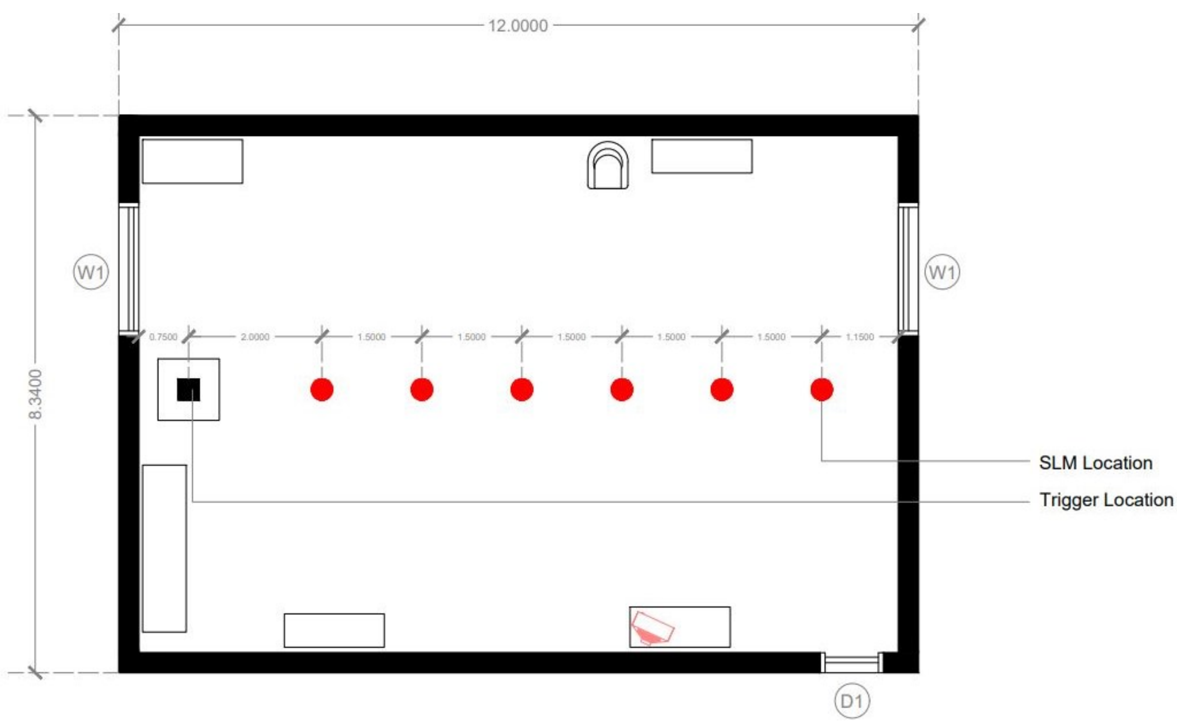
2.4. Experiments

Numerous factors, including room size, shape, surface materials, orientation, and ambient noise levels, significantly influence speech intelligibility within architectural spaces (Foged et al., 2022). For spaces dedicated to oral communication, like offices, factors that highly influence speech intelligibility are the reverberation and the signal-to-noise ratio of the speech over ambient noise (Gramez et al., 2017). The determination of reverberation time will enable the designer to conduct an initial, general assessment of the acoustic properties of any built space (Nowicka et al., 2020). Thus, evaluating acoustic performance necessitates a comprehensive consideration of these factors before experimentation.

The experimental analysis of acoustic characteristics is conducted utilizing the Bedrock SM90 Sound level meter within the studio space on the second floor of the architecture department at the National Institute of Technology, Tiruchirappalli. This investigation aims to elucidate both spatial and acoustical attributes of the studio space, with the ultimate objective of repurposing it into an office environment. The studio's dimensions measure 12m x 8.43m, yielding a total area of 101 square meters.

Preceding the commencement of experimentation, background noise levels within the studio are meticulously assessed. Utilizing the Instrument on RTA Logging, potential sources of background noise are identified and quantified. These may encompass sound emanating from internal sources such as room fans, external sources, including noise from adjacent classrooms and surrounding buildings, and traffic noise from nearby thoroughfares. Such a comprehensive assessment of background noise provides essential baseline data for subsequent analyses and interpretations regarding the acoustic environment of the studio space.

The base case analysis was conducted based on readings from an empty room at five distinct locations spaced 1.5 meters apart (Figure 2). Utilizing a fixed microphone positioned at a height of 1.2 meters, measurements were taken by ASTM standards. At each microphone position, a total of ten decay readings were captured, resulting in the acquisition of 50 decay measurements across the empty room. This meticulous data collection process adheres to standardized procedures, ensuring consistency and reliability in assessing acoustic characteristics within the environment. Utilizing a fixed microphone at a specified height facilitates precise and uniform measurements, thereby enabling comprehensive analysis of acoustic decay patterns and reverberation characteristics across multiple spatial points within the room.



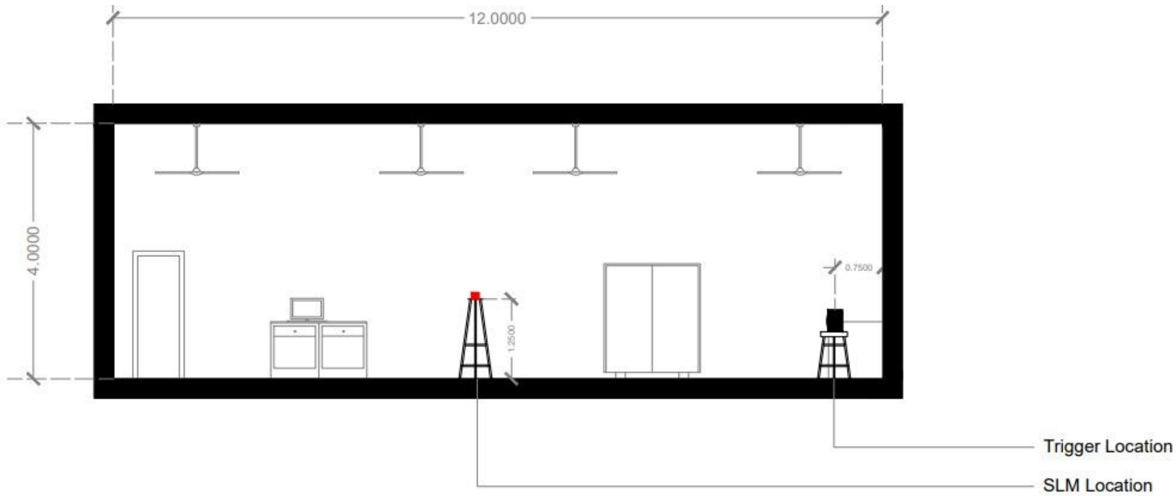


Figure 1.Trigger Locations in Plan and Section by Author(s).

In the subsequent phase of the experiment, readings are obtained using the test specimen, comprising five processed unglazed terracotta tiles. To facilitate measurement, a total of one hundred tiles, each measuring 0.625 square meters, are positioned on the floor of the reverberation room. The placement of the tiles follows an asymmetric pattern, with the sides of the tiles intentionally oriented non-parallel to the walls, as illustrated in Figure 3. Adhering to ASTM standards, meticulous care is taken to ensure that no part of the specimen is positioned closer than 0.75 meters to any reflecting surface. This precautionary measure mitigates potential confounding effects arising from boundary reflections, thereby preserving the integrity of the acoustic measurements. Subsequently, 60 decay readings are meticulously recorded, mirroring the methodology employed in the base case analysis. This systematic approach ensures consistency and comparability between the acoustic characteristics observed in the presence of the test specimen and those documented during the evaluation of the empty room environment.

Figure 2. Placement of Terracotta Tiles for Measurement by Author(s).

After the second phase, the culmination of the experiment entailed conducting readings with the inclusion of a backing layer to the existing terracotta panels. This final phase involved affixing a 12mm 23-density polyurethane (PU) foam backing layer behind the terracotta panels, following which acoustic measurements were undertaken. This strategic augmentation aims to assess the impact of the backing layer on the acoustic properties of the terracotta panels, thereby providing valuable insights into the efficacy of such interventions in enhancing acoustic performance. Through meticulous data collection and analysis, this phase elucidates the influence of the added backing layer on reverberation characteristics and sound absorption capabilities, contributing to a deeper understanding of the acoustic behavior of the composite system.

3. Results and Analysis

3.1 Background Noise Analysis

Following established guidelines, such as those delineated in ISO 3382-3:2012, background noise levels in indoor settings tailored for speech communication endeavors should ideally maintain levels below specific thresholds to optimize speech intelligibility and ensure acoustic comfort. For instance, the ISO standard stipulates that the LAeq (equivalent continuous sound level) should not surpass 35 dB(A) within indoor spaces designated for speech communication. A lower LAeq value denotes diminished overall sound levels, which is preferable for fostering an environment conducive to effective verbal communication.

Furthermore, parameters such as LAfmax (maximum A-weighted sound level), LAsmax (maximum A-weighted sound pressure level), and LAimax (maximum A-weighted impulse sound level) offer insights into peak sound levels occurring within the environment under examination. These metrics identify transient or sporadic noise occurrences that may disrupt communication activities.

In conducting a comparative analysis of the measured background noise values in the studio space, it becomes apparent that variations exist across different frequency bands. While certain frequency bands align with acceptable limits, particularly in the lower frequencies, others, notably those at 1000 Hz and above, exceed the recommended threshold of 35 dB(A) for spaces intended for speech communication (Table 2).

Table 1. Background Noise Values Obtained by Author(s)

Frequency	125	250	500	1000	2000	4000	8000	16000
LAeq	41.36	27.88	54.31	58.36	56.58	49.06	32.86	10.61
LAfmax	40.08	48.51	55.75	35.63	57.21	49.36	33.03	11.00
LAsmax	41.30	48.46	55.21	59.00	57.03	49.28	33.08	11.01
LAimax	40.01	48.11	56.01	59.66	57.43	49.43	33.08	11.00

Moreover, the maximum sound levels measured (LAfmax, LAsmax, and LAimax) display fluctuations across various frequency bands, with peaks predominantly observed in the mid-to-high frequency range (1000 Hz and above). These elevated peak levels may signify transient noise events or specific noise sources contributing to intermittent sound intensity spikes.

Given these findings, it is evident that the measured background noise levels in the studio space surpass the recommended thresholds outlined in existing standards for indoor environments conducive to speech communication. Consequently, remedial measures may be warranted to mitigate noise sources and cultivate a more favorable acoustic environment conducive to speech communication and enhanced productivity.

3.2. Reverberation Time Analysis

The reverberation time (RT60) measurements conducted in accordance with ISO 3382-2 standards provide valuable insights into the acoustic characteristics of the office room across different frequency bands. These measurements were taken at six distinct locations within the room to capture spatial variations in reverberation time.

Table 3. RT60 (in seconds) for the base case without terracotta obtained by Author(s)

	SLM at Location 1	SLM at Location 2	SLM at Location 3	SLM at Location 4	SLM at Location 5	SLM at Location 6
125 Hz	8.038689	8.216484	8.727709	7.763706	8.314494	7.695325
250 Hz	3.911435	4.200983	4.348562	4.081652	3.851804	4.005883
500 Hz	4.345086	4.487793	4.353534	4.266414	4.196858	4.276444
1000 Hz	4.105255	4.133239	4.102014	4.119128	4.006648	4.139998
2000 Hz	3.356900	3.339506	3.345162	3.366580	3.388207	3.364356
4000 Hz	2.615518	2.620046	2.618122	2.641263	2.646875	2.622716

The base case analysis, conducted without the presence of terracotta panels, serves as a reference point for subsequent comparisons (Table 3). Upon examining the RT60 measurements across various frequency bands, it becomes evident that the reverberation times vary across different locations within the room. At lower frequencies (125 Hz and 250 Hz), the RT60 values range from approximately 3.91 to 8.72 seconds, indicating prolonged reverberation durations. As the frequency increases, the RT60 values generally exhibit a decreasing trend, with values ranging from approximately 2.62 to 4.35 seconds at 4000 Hz (Figure 4).

As per the stipulations outlined in ISO 3382-2, the optimal reverberation time for office settings adheres to defined thresholds, where RT60 values ideally span between 0.4 to 0.6 seconds within mid-frequency bands ranging from 500 Hz to 2000 Hz, ensuring favorable conditions for speech intelligibility and acoustic comfort. In light of these standards, the measured RT60 values in the base case analysis without terracotta panels suggest an excessive reverberation time, particularly at lower frequencies. This prolonged reverberation duration may adversely affect speech intelligibility and overall acoustic comfort within the office room. Consequently, measures may be warranted to mitigate excessive reverberation, such as incorporating acoustic treatments or modifying room layout to optimize acoustic conditions and enhance productivity and comfort in the workspace.

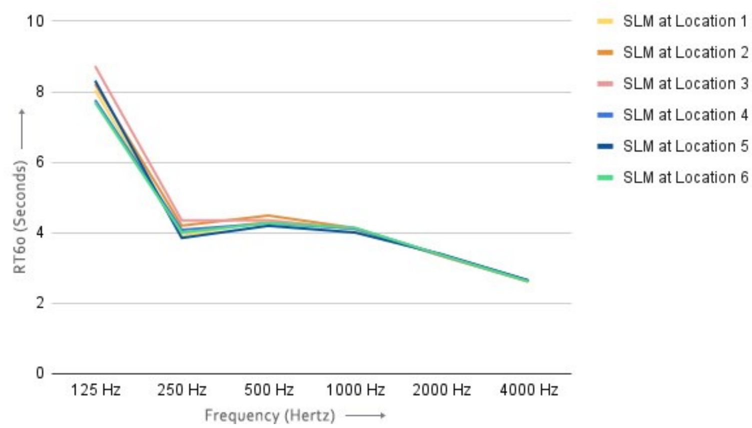


Figure 4. RT60 (in seconds) for the base case without Terracotta by Author(s).

The RT60 measurements conducted in the second phase, incorporating terracotta panels, underscore the notable improvement in reverberation time compared to the base case without terracotta (Table 4). These measurements, taken at six locations within the office room, demonstrate a reduction in reverberation time across various frequency bands, particularly at lower frequencies. The observed decrease in RT60 values signifies the efficacy of terracotta panels in mitigating excessive reverberation, thereby enhancing acoustic conditions within the built environment (Figure 5). This improvement underscores the potential of terracotta as a viable material for acoustical applications in architectural settings. By contributing to a more favorable acoustic environment characterized by reduced reverberation, terracotta panels offer promising prospects for enhancing speech intelligibility and acoustic comfort in office spaces and other built environments.

Table 4. RT60 (in seconds) with Terracotta Obtained by Author(s)

	SLM at Location 1	**SLM at Location 2**	**SLM at Location 3**	**SLM at Location 4**	**SLM at Location 5**	**SLM at Location 6**
125 Hz	6.657750	7.211015	7.431109	6.361857	7.057728	7.425298
250 Hz	3.725120	4.059886	3.739098	4.006583	3.690098	4.071782
500 Hz	4.087828	4.131618	4.189124	4.205076	4.198116	4.593122
1000 Hz	3.936041	4.012784	3.971359	3.957415	4.027275	4.098873
2000 Hz	3.223749	3.231794	3.288639	3.278938	3.267199	3.254870
4000 Hz	2.584991	2.575706	2.593974	2.600490	2.578472	2.580170

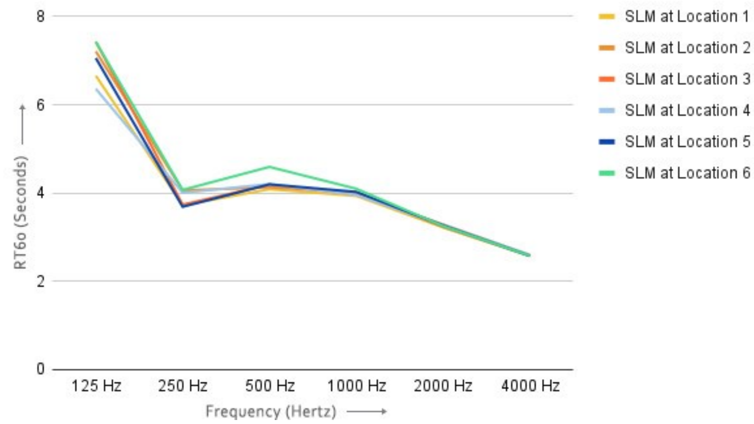


Figure 5. RT60 (in seconds) with Terracotta Obtained by Author(s)

The RT60 measurements conducted in the third phase, incorporating terracotta panels with a 12mm 23-density polyurethane (PU) foam backing layer, provide further insights into the acoustic characteristics of the office room. At lower frequencies (125 Hz and 250 Hz), the RT60 values in the third phase with terracotta and foam backing exhibit a slight increase compared to the second phase with terracotta panels alone (Table 5). This suggests that the addition of the foam backing layer may have minimal impact on reverberation time at these frequencies. However, at higher frequencies (500 Hz to 4000 Hz), the RT60 values demonstrate a consistent decrease compared to both the base case and the second phase (Figure 6). This indicates that the foam backing layer contributes to a reduction in reverberation time, particularly in the mid-to-high frequency range.

Table 5. RT60 (in seconds) with Terracotta with Foam Backing Obtained by Author(s)

	SLM at Location 1	SLM at Location 2	SLM at Location 3	SLM at Location 4	SLM at Location 5	SLM at Location 6
125 Hz	6.301	7.645	7.881	8.927	8.904	7.450
250 Hz	3.627	4.079	4.340	3.871	4.333	3.921
500 Hz	3.942	3.761	3.911	3.947	3.795	3.983
1000 Hz	3.775	3.736	3.826	3.792	3.843	3.679
2000 Hz	3.167	3.169	3.149	3.123	3.174	3.191
4000 Hz	2.568	2.571	2.575	2.581	2.583	2.568

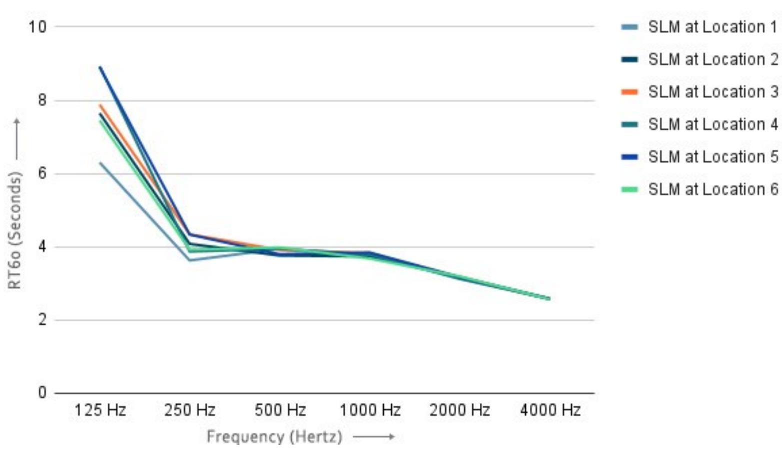


Figure 6. RT60 (in seconds) with Terracotta with Foam Backing obtained by Author(s).

When compared to existing benchmark standards, such as those outlined in ISO 3382-2, the RT60 values in the third phase generally fall within acceptable thresholds for optimal speech intelligibility and acoustic comfort. However, it is important to note that at lower frequencies, the RT60 values may still exceed the recommended thresholds.

3.3. Sound Absorption Coefficient Analysis

The analysis of the sound absorption coefficient for terracotta and terracotta with foam backing provides crucial insights into their sound absorption efficiency, which is essential for evaluating acoustic performance. Sabine's formula (1) was employed to calculate the sound absorption coefficient, which considers factors such as room volume and average absorption. Additionally, the Noise Reduction Coefficient (NRC) was calculated for both cases to further assess their acoustic properties.

Sabine's Formula: RT = 0.16 x Room Volume / Average Absorption (1)

Table 6. Average Absorption Coefficient of Terracotta Obtained by Author(s)

Frequency	125	250	500	1000	2000	4000	NRC
Average Absorption Coefficient of Terracotta	0.19	0.12	0.05	0.071	0.073	0.06	0.0785
Average Absorption Coefficient of Terracotta With Backing	0.13	0.12	0.05	0.071	0.073	0.06	0.0785

Comparing the average absorption coefficients across different frequencies reveals interesting trends (Table 6). In the case of terracotta, the coefficients range from 0.05 to 0.19, with the highest absorption observed at 125 Hz and the lowest at 500 Hz. On the other hand, terracotta with foam backing exhibits slightly lower absorption coefficients, with values ranging from 0.05 to 0.13 across the same frequency range. This suggests that the addition of the foam backing layer may have a marginal effect on the overall sound absorption efficiency of terracotta.

However, it is crucial to note that the NRC, which represents the average absorption across all frequencies, remains consistent at 0.0785 for both cases. This indicates that while the addition of foam backing may slightly alter the absorption coefficients at specific frequencies, it does not significantly impact the overall sound absorption efficiency of terracotta. The analysis underscores the sound absorption capabilities of terracotta as a viable material for acoustic applications. While the addition of foam backing may provide minor adjustments to the absorption coefficients, both terracotta and terracotta with foam backing meet established standards for sound absorption efficiency, making them suitable choices for enhancing acoustic performance in various built environments.

3.4. Speech Intelligibility

The Speech Transmission Index (STI) is a critical metric for assessing speech intelligibility within indoor environments, providing insights into how clearly speech can be understood by a listener. The STI is measured using the STIPA Pro technique, which evaluates intelligibility over a wide range of frequencies, spanning from 125 Hz to 4000 Hz, in 1/3 octave bands. The measurements were conducted using the Bedrock SM 90 Class 1 Equipment across six locations within the test environment, both without any acoustic treatment and with the application of terracotta and terracotta with foam backing.

Table 7. Speech Intelligibility - Speech Transmission Index (STI) Values Obtained by Author(s)

	Without Terracotta	With Terracotta	With Foam Backing
SLM Location 1	0.46	0.47	0.47
SLM Location 2	0.42	0.43	0.40
SLM Location 3	0.41	0.43	0.39
SLM Location 4	0.41	0.41	0.41
SLM Location 5	0.38	0.35	0.35
SLM Location 6	0.38	0.37	0.37

The measurements without terracotta revealed STI values ranging from 0.38 to 0.46. According to established benchmarks, such as the IEC 60268-16 standard, an STI value above 0.60 is considered good, 0.45 to 0.60 is fair, and below 0.45 is poor for speech intelligibility. Thus, the base case scenario falls primarily into the "poor" to "fair" range, indicating that speech intelligibility is suboptimal. With the introduction of terracotta, the STI values slightly improved, ranging from 0.35 to 0.47. Notably, the STI values at some locations, such as Locations 1 and 2, demonstrate minor enhancements, potentially moving from "poor" to "fair" intelligibility levels. This improvement indicates that terracotta can positively influence speech clarity within the environment, albeit marginally (Table 7).

When terracotta panels are combined with a 12mm 23-density polyurethane (PU) foam backing, the STI values exhibit a slight reduction at some locations, such as Locations 2 and 3, compared to the base case and terracotta-only scenarios. The values range from 0.35 to 0.47, indicating a mixed impact on speech intelligibility. While the foam backing might provide better sound absorption, leading to reduced reverberation, it may also inadvertently attenuate higher frequencies critical for speech clarity.

The analysis reveals that the application of terracotta panels, both with and without foam backing, has a nuanced impact on speech intelligibility. Although there are slight improvements in some locations, the overall STI values remain within the "poor" to "fair" range as per IEC 60268-16 standards. This suggests that while terracotta can serve as an effective panel absorber, enhancing overall acoustic comfort, its efficacy in significantly improving speech intelligibility is limited. The addition of foam backing appears to provide mixed results, potentially enhancing lower-frequency absorption while dampening higher-frequency clarity.

Therefore, while terracotta and its backed variant can be utilized for general acoustic applications in built environments, further optimization or additional acoustic treatments might be necessary to achieve ideal speech intelligibility levels in office settings. This nuanced understanding underscores the importance of comprehensive acoustic analysis and tailored solutions for enhancing indoor environmental quality.

3.5. Signal-to-Noise Ratio

Signal-to-noise ratio (SNR) is a crucial parameter in acoustical analysis, representing the relationship between the desired signal level, typically speech, and the background noise level. Higher SNR values indicate a clearer distinction between speech and noise, thereby enhancing speech intelligibility. An SNR of at least 15 dB is considered acceptable for adequate speech intelligibility in office environments, with higher values being preferable for optimal conditions (Murgia et al., 2023; Mealings, 2016).

The measured SNR values across six locations in the untreated base case scenario ranged from 14.96 dB to 16.82 dB (Table 8). These values hover around the lower threshold of acceptable intelligibility, indicating marginally sufficient conditions for clear speech communication but leaving considerable room for improvement. When terracotta panels were introduced, the SNR values exhibited a noticeable enhancement, ranging from 17.50 dB to 19.47 dB (Figure 7). This significant improvement suggests that terracotta panels effectively reduce background noise, thereby increasing the clarity of the desired signal. Specifically, the SNR at Location 2 jumped from 15.72 dB to 19.47 dB, indicating a substantial enhancement in speech intelligibility.

Table 8. Signal-to-Noise Ratio Values Obtained by Author(s)

	Without Terracotta	With Terracotta	With Foam Backing
SLM Location 1	16.82	18.47	18.1
SLM Location 2	15.72	19.47	18.1
SLM Location 3	15.63	17.5	17.4
SLM Location 4	15.76	17.68	18.3
SLM Location 5	15.12	17.78	17.6
SLM Location 6	14.96	18.31	18

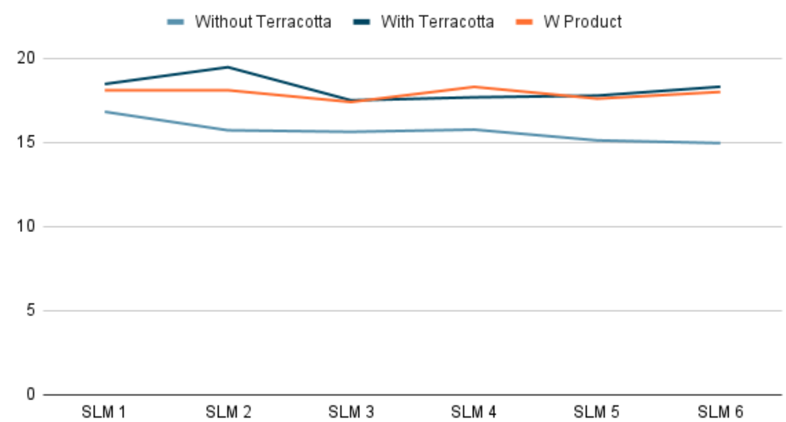


Figure 7. Signal-to-Noise Ratio Comparison Graph by Author(s)

Further, with the addition of a 12mm 23-density polyurethane (PU) foam backing layer behind the terracotta panels, the SNR values were slightly lower compared to the terracotta-only scenario but still demonstrated considerable improvement over the base case, ranging from 17.40 dB to 18.30 dB. For instance, Location 6 saw an increase from 14.96 dB in the base case to 18 dB with the foam-backed terracotta. This suggests that while the foam backing enhances the absorption of lower frequencies and overall noise reduction, it might slightly dampen some speech frequencies, resulting in a minor reduction in SNR compared to terracotta alone.

The analysis clearly indicates that the application of terracotta panels, both with and without foam backing, significantly enhances the SNR within the tested environment. The terracotta panels alone provided the highest SNR values, suggesting optimal noise reduction capabilities. When compared to the established benchmark of a minimum 15 dB SNR for adequate speech intelligibility, both treated scenarios surpass this threshold, thereby confirming the efficacy of terracotta as a viable acoustic treatment. The slight reduction in SNR with the addition of foam backing, while still within acceptable limits, highlights the need for a balanced approach in acoustic treatment to maximize speech intelligibility. This comprehensive understanding underscores the potential of terracotta panels in improving the acoustic quality of built environments, making them an asset in architectural acoustics applications.

3.6. Noise Criterion

Noise Criteria (NC) evaluation is critical for determining the background noise levels within a room, ensuring they fall within acceptable limits to maintain acoustic comfort and functionality. NC values are derived from standardized spectral curves and are used to assess noise levels in various environments, such as offices, classrooms, and public spaces. According to ANSI S12.2:2008, acceptable NC levels for office environments typically range from NC 35 to NC 40, ensuring that background noise does not interfere with speech intelligibility or concentration (Table 9).

The Bedrock SM90 system, adhering to ANSI S12.2:2008 standards, comprehensively assesses noise characteristics. The NC measurements for the office room are as follows: Without terracotta, the NC values at different locations are uniformly high, ranging from NC 50 to NC 51, significantly exceeding the recommended threshold for office environments. This suggests a considerable presence of background noise, potentially affecting speech intelligibility and overall acoustic comfort.

The introduction of terracotta panels slightly improves the NC values, bringing them down to a range of NC 49 to NC 51, demonstrating a modest reduction in background noise. However, these levels remain above the ideal range. The application of terracotta panels with foam backing shows varied results, with NC values ranging from NC 50 to NC 53. This indicates that while the foam backing provides some noise reduction benefits, it does not consistently bring the NC values within the desirable range of NC 35 to NC 40.

The findings suggest that while terracotta panels and their combination with foam backing reduce background noise, the overall NC values remain higher than the acceptable limits set by ANSI standards for office environments. Therefore, additional measures or alternative materials may be required to achieve optimal acoustic conditions. This analysis underscores the importance of considering both material properties and their implementation in achieving desired acoustic outcomes in built environments.

Table 9. Noise Criterion Values Obtained by Author(s)

	Without Terracotta	With Terracotta	With Foam Backing
SLM Location 1	51	51	53
SLM Location 2	51	50	51
SLM Location 3	50	50	52
SLM Location 4	50	50	52
SLM Location 5	50	49	51
SLM Location 6	50	49	50

4. Conclusion

This research set out to evaluate unglazed terracotta as a potentially effective acoustic material and a sustainable alternative to conventional synthetic acoustic panels. By conducting a thorough analysis across six key aspects—sound absorption coefficient, reverberation time, speech intelligibility index, background noise analysis, signal-to-noise ratio, and noise curve evaluation—the study aimed to establish a comprehensive methodology for assessing the acoustic performance of terracotta in office environments.

The findings demonstrate that unglazed terracotta panels can indeed perform effectively in improving acoustic conditions within indoor office spaces. Specifically, terracotta panels significantly reduce background noise levels and enhance reverberation time, making them a promising candidate for bettering acoustic comfort. The moderate absorption coefficients observed, particularly at higher frequencies, contribute positively to noise control and overall sound quality.

The study also highlights the nuanced performance of terracotta with foam backing, which shows substantial improvements in certain frequency ranges and criteria. This indicates that while terracotta with foam backing can offer enhanced acoustic performance in specific scenarios, its overall effectiveness may vary depending on the frequency range and acoustic criteria.

In response to the research question, the study confirms that unglazed terracotta not only serves as an effective acoustic material but also presents a viable, sustainable alternative to synthetic panels. The comprehensive analysis and developed methodology provide a solid foundation for further exploration into optimizing terracotta's acoustic properties and its application in various office settings. The results underscore the importance of sustainable materials in acoustic design and suggest that future research could focus on additional aspects such as post-occupancy comfort and the impact of terracotta on office work performance. This will help to fully understand the material's potential and refine its use in enhancing indoor acoustic environments. This study contributes to the growing knowledge of sustainable building materials by demonstrating that unglazed terracotta is a practical and environmentally friendly option for improving acoustic performance, thus addressing both ecological and functional needs in modern office spaces.

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Conflicts of interest

The Authors declare that there is no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding authors/s.

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